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Topology optimization for the radiation and scattering of sound from thin-body using genetic algorithms

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Abstract

Many industrial applications generally use thin-body structures in their design. To calculate the radiation and scattering of sound from a thin-body structure, the conventional boundary element method (BEM) using the Helmholtz integral equation is not an effective resolution. Especially, if the structure including a thin-body is not fully closed, the conventional BEM fails to yield a reliable solution. Unfortunately, most applications requiring the noise prediction generally have some openings because of cooling and so on. Therefore, many researchers have studied to resolve the thin-body problem in various fields. In engineering optimization fields, even though several studies have been made on the design optimization to improve the acoustic characteristic of a closed structure by using the conventional BEM, no study has been yet reported for the design of the holes on the thin-body using topology optimization.

In this research, the normal derivative integral equation is used to solve the acoustic problem of a thin-body structure. Also, based on the normal derivative integral equation, the topology optimization of the thin-body has been studied for the design of the holes. An in-house code, acTop, is developed and implemented for the acoustical topology optimization using a genetic algorithm. By using a simple box example, the utility of acTop is validated. The results of examples show that acTop can provide very good initial design for acoustic problems. Therefore, the proposed topology optimization technique should be attractive for a design engineer in acoustic fields.

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1. Introduction

Thin-body structures are frequently used for the design of many industrial applications such as fins or opened shells. To solve the acoustic problem including thin bodies, the conventional BEM using the Helmholtz integral equation is not an effective method because the mesh on one side of a thin-body is too close to the mesh on the opposite side. Although that difficulty can be overcome by using very fine meshes, the process requires too much preprocessing and calculation time. Moreover, the nearly singular problem may occur in the integral equation. Thus, many researchers have tried to solve the thin-body problem in various physical fields including acoustics, electromagnetics and solid mechanics.

Theoretically, the simplest way to handle the thin-body problem is the multi-domain BEM [1], in which an imaginary interface surface is constructed to divide the acoustic domain into an interior subdomain and an exterior subdomain. Each subdomain has a well-defined boundary surface so that the conventional BEM can be applied. The sound pressure and normal velocity are then matched at the interface surface. Even though the concept of multi-domain BEM is simple and straightforward, it is not very efficient in computation when the imaginary interface surface is relatively large. In the normal derivative integral equation, proposed by Wu and Wan [2], an imaginary interface surface is also constructed like the multi-domain BEM. Furthermore, the Helmholtz integral equations and the normal derivative integral equations are constructed for each subdomain including both a structural surface and an imaginary surface. The integrals over the imaginary interface surface, however, are simply canceled out due to continuity of pressure and velocity. Therefore, only the neutral surface of the thin-body remains for the discretization. But the normal derivative integral equation approach, however, involves the evaluation of a hyper-singular integral in order of $1/r^3$. So the regularization method, originally derived by Maue [3] and later by Mitzner [4], is utilized. The evaluation of the hyper-singular integral can be also avoided by adopting a variational formulation, proposed by Wu et al. [5]. The resulting coefficient matrix obtained from the variational formulation is symmetric, but the computational cost is relatively high because a double surface integral must be evaluated.

In structural topology optimization, an artificial material density varying between 0 and 1 is used as a design variable. The term ‘topology optimization’ is often confused with ‘layout optimization’. Rozvany [6] stated the identical meaning for those terms in his work. Major portion of researches in structural layout optimization had been confined to a truss-like problem before Bendsoe and Kikuchi [7] set up a remarkable milestone in history of the structural topology optimization by using a homogenization method. While the homogenization method geometrically represents effective material properties, the density method uses Young’s modulus as a design variable. Although it does not guarantee the optimal solution, a lot of recent studies adopt the density method due to not only its simplicity in formulation and implementation but also less memory requirement and computation time. Wang [8] used the density method to obtain an optimal topology of an automobile part for a vibration problem.

In recent years, topology optimization has been expanded to various fields. Sigmund [9] proposed micro-thermal-actuator design and Nishiwaki et al. [10] presented flextensional actuators using piezoceramic device. Also, Wang and Kang [11] presented the topology optimization of electromagnetic systems. No study in the topology optimization for the acoustics, however, has been reported. Even though several studies have been made on acoustic optimization, for example Cunefare et al. [12], Wang and Lee [13] presented the sizing optimization using the design sensitivity analysis through chain-ruled derivatives from the finite element method and boundary element method, all of them discussed only the sizing and shape optimization. Moreover, their researches support only closed structures because they used Helmholtz integral equation. If the structures have holes, the previous researches in acoustic optimization fail to get the reliable solution. In general, most applications have openings. For instance, the instruments such as guitar and violin have holes for the resonance, and computer case also has holes for cooling. For those kinds of applications, the topologies of the holes are very important for their acoustic characteristics.

In this research, the topology optimization technique to design holes for the radiation and scattering from thin-body structures is proposed by using the normal gradient integral equation and the genetic algorithms [14]. The normal derivative integral formulation is used for the acoustic analysis of the thin-body and the genetic algorithm is adopted as an optimization algorithm. As a numerical example, a simple box is considered to validate the accuracy and efficiency of the proposed topology optimization technique in this research for both radiation and scattering of sound. For the validation of the results, the commercial acoustic analysis program SYSNOISE is used.

2. Normal derivative integral equation

The normal derivative integral equation, proposed by Wu and Wan [2], has two formulations to solve the thin-body acoustic problems. The first equation is

$$\int_S \frac{\partial G(\hat{x},\hat{y})}{\partial \mathbf{n}}(p_s^+(\hat{y}) - p_s^-(\hat{y}))\,\mathrm{d}S + p_I = \begin{cases} p(\hat{x}), & \hat{x} \text{ not on } S, \\ c(\hat{x})p^+(\hat{x}) + c^0(\hat{x})p^-(\hat{x}), & \hat{x} \text{ on } S. \end{cases} \tag{1}$$

In Eq. (1), point $\hat{y}$ is located on the surface, $G(\hat{x},\hat{y})$ is the Green function, which is the function of distance r between the points $\hat{x}$ and $\hat{y}$, $\mathbf{n}$ is the normal vector of the surface, $c(\hat{x})$ and $c^0(\hat{x})$ are constants that depend on the point $\hat{x}$ where $c(\hat{x})$ is one for $\hat{x}$ in Ω^+ and zero for $\hat{x}$ in Ω^-, and $c^0(\hat{x})$ is zero for $\hat{x}$ in Ω^+ and one for $\hat{x}$ in Ω^- as shown in Fig. 1. If $\hat{x}$ is on the boundary surface S and there is a unique tangent plane at $\hat{x}$, both $c(\hat{x})$and $c^0(\hat{x})$ are equal to 1/2. When the field point $\hat{x}$ is located out of the surface, Eq. (1) is rewritten with the double layer potential μ, which is the difference between outside and inside pressures on the surface and is called the jump of pressure:

$$\int_S \frac{\partial G}{\partial \mathbf{n}}\mu\,\mathrm{d}S + p_I = p(\hat{x}). \tag{2}$$

It should be noted that Eq. (2) itself is not sufficient to solve the problem because it contains two unknowns, μ and $p(\hat{x})$. Since the $p(\hat{x})$ is a solution of equation, the double layer potential has to be obtained from an additional equation. Moreover, the normal velocity of the thin body, which is usually the boundary condition in a radiation or scattering problem, is not included in the equation. Hence, another integral equation containing the normal velocity of the thin body is

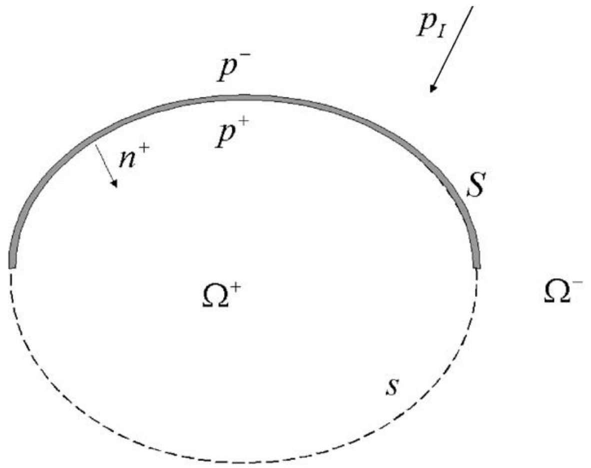

Fig. 1. Radiation and scattering of sound from a thin-body.

needed to supplement Eq. (2). This second equation is

$$\frac{\partial p(\hat{x})}{\partial \mathbf{n}_{\hat{x}}} = -\mathrm{j}\omega\rho\mathbf{v}_n(\hat{x}) = \int_S \{(\mathbf{n}_{\hat{x}} \times \nabla_{\hat{x}} G) \cdot (\mathbf{n} \times \nabla\mu) + k^2(\mathbf{n}_{\hat{x}} \cdot \mathbf{n})G\mu\}\,\mathrm{d}S + \frac{\partial p_I}{\partial \mathbf{n}_{\hat{x}}}. \tag{3}$$

It is known that a differentiation of Helmholtz equation in the normal direction will lead to a hyper singular integral in the order of $1/r^3$. Hence a regularized normal derivative integral equation proposed by Maue [3] and Mitzner [4] is adopted in Eq. (3). The radiated pressure $p(\hat{x})$ can be calculated from Eq. (2) with the value of double layer potential μ obtained from Eq. (3) with the known normal velocities $\mathbf{v}_n$ on the surface S. The numerical solution of Eqs. (2) and (3) can be obtained by discretizing the surface S of the thin-body structure into a number of elements. Using interpolating a shape function, Eqs. (2) and (3) can be discretized and rewritten in a matrix form

$$\mathbf{p}(\hat{x}) = \mathbf{M}_e\boldsymbol{\mu} + \mathbf{C}_1 p_I, \tag{4}$$

$$-\mathrm{j}\omega\rho\mathbf{v}_n = \mathbf{M}\boldsymbol{\mu} + \mathbf{C}_1\frac{\partial p_I}{\partial \mathbf{n}_{\hat{x}}}. \tag{5}$$

In Eqs. (4) and (5), $\mathbf{C}_1$ is a column vector whose every element is one, $\mathbf{p}(\hat{x})$ is the pressure at field points, μ is a column vector composed by the values of double layer potential on the discretized surface, and $\mathbf{M}_e$ is the contribution matrix. $\mathbf{M}$ and $\mathbf{v}_n$ are the system matrix and the normal velocity vector, respectively.

3. Optimization formulation

3.1. Problem definition for the topology optimization

Etymologically, the word *topology* is derived from the Greek noun *topos*, which means location, place, space or domain. The topology of a structure, i.e., the arrangement of material or the positioning of structural elements, is crucial for its optimality. It is of great importance for the development of new products to find the best possible layout for given objectives and constraints at a very early stage of the design process. Traditionally, most studies in topology optimization have been devoted to compliance minimization of linear elastic structures. During this period, the researchers have been mainly occupied with two different kinds of topology design processes, the material technique and the geometrical technique, relied on gradient-based method. The detail information about previous research of topology optimization can be referred to a review paper by Eschenauer and Olhoff [15].

Basically, the gradient-based optimization requires design sensitivities of a performance with respect to the design variables. In solid mechanics, the actual design variable for the design sensitivity is not an existence of element but an artificial material property related to Young's modulus or density of the element. The optimizer regulates the density (or Young's modulus) by iterative calculations using sensitivity coefficients and eliminates the elements by degrees, which has relatively low density. Unfortunately, in acoustics, it is difficult to utilize the traditional topology optimization scheme in the structural systems. The system matrix of an acoustic formulation depends on the frequency and the position of the structure only. Even if fluid properties such as fluid density and sound velocity are used in the acoustic analysis, those are independent of the structure. In acoustic topology optimization, there is no structural parameter substituting for the existence of elements and only the existence of each element itself can be a design variable. Therefore, the acoustic topology optimization is defined as an integer problem, i.e., exist or not.

Because of the above difficulty, in this research, the topology optimization technique is developed to find the best topology of the holes on the thin-body structure using the genetic algorithm instead of the gradient-based method.

3.2. Basics of genetic algorithms

Genetic algorithms (GAs) are robust stochastic global optimization procedures for finding the global minimum (or maximum) of a multi-modal function defined in the search space. Especially, the GA is one of the efficient integer-programming techniques like the simulated annealing method. GAs are inspired by certain rules from biology. In a biological organism, the structure that encodes the prescription that specifies how the organism is to be constructed is called as a chromosome. In general, many chromosomes are required to specify the complete organism. The complete set of chromosomes is called a genotype, and the resulting organism is called a phenotype. Each chromosome comprises a number of individual structures called genes. Each gene encodes a particular feature of the organism and the location (or locus) of the gene within the chromosome structure and determines what particular characteristic the gene represents.

In the implementation, the GA requires the natural parameter set of the optimization problem to be coded as a finite-length string containing alphanumeric characters. This string is recognized as an artificial gene. The GA starts with a population of randomly selected strings. Describing the actual GA requires only a few statements:

(i) Begin with a population of individuals generated at random.
(ii) Determine the fitness of each individual in the current population.

(iii) Select parents for the next generation with a probability proportional to their fitness.
(iv) Mate the selected parents to produce offspring to populate the new generation.
(v) Repeat item (ii)–(iv).

After selection, various genetic operators such as Crossover, Mutation and Reproduction are used to extract common properties shared by the two good strings, which are then mated and used to provide selected offspring for the next generation. (Fig. 1).

3.3. Topology optimization for thin-body acoustics

The weakest point of using the GA is that too much calculation time is required due to many function evaluations in the iterative procedures of the optimization. Moreover, each acoustic analysis needs much calculation time to construct matrices. This disadvantage, however, is not serious for the topology optimization of the holes used in this research because the every information of the element matrix can be obtained by just one time's analysis. Most numerical methods construct the global matrix by accumulation of the element matrices, as shown in Fig. 2. In solid mechanics, the element matrices have to be recalculated for each chromosome in the iterative procedures of optimization since the element matrices are the function of design variables such as the stiffness and the density. The element matrices used in acoustic analysis, however, do not vary unless the shape of structure is changed, because the acoustic formulation depends only the position of the structure and frequency. Hence the reconstruction of global matrix needs just sums in simple addition of element matrices calculated at the beginning stage. When a commercial code is used for the analysis, calculation of the each element matrix is required for every function evaluation because the information of element matrix is not supplied.

If the three-dimensional variable arrays of the element matrices are known, then the reconstruction of the global matrix for each chromosome is very simple addition of every layer except the layers of eliminated elements. Since the almost calculation time for the acoustic analysis is used to calculate the element matrices, the function evaluation of the new population in the GA does not require so much time for the acoustic analysis.

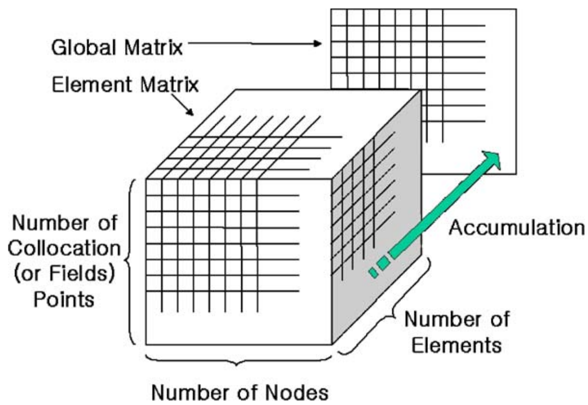

Fig. 2. Construction of global matrix from element matrix.

Based on the normal derivative integral formulation, Eqs. (4) and (5), and the GA, the acoustic topology optimization program (acTop) is developed. The flow chart of acTop appears in Fig. 3. Since acTop has no preprocessor, the elementary model of the object structure has to be modeled and discretized by using a commercial program such as MSC/PATRAN. A design space of the elementary model, surfaces on which the holes will be made, has to be closed. Numerical data of the elementary model, such as the position of nodes, the connectivity of elements, and so on, are

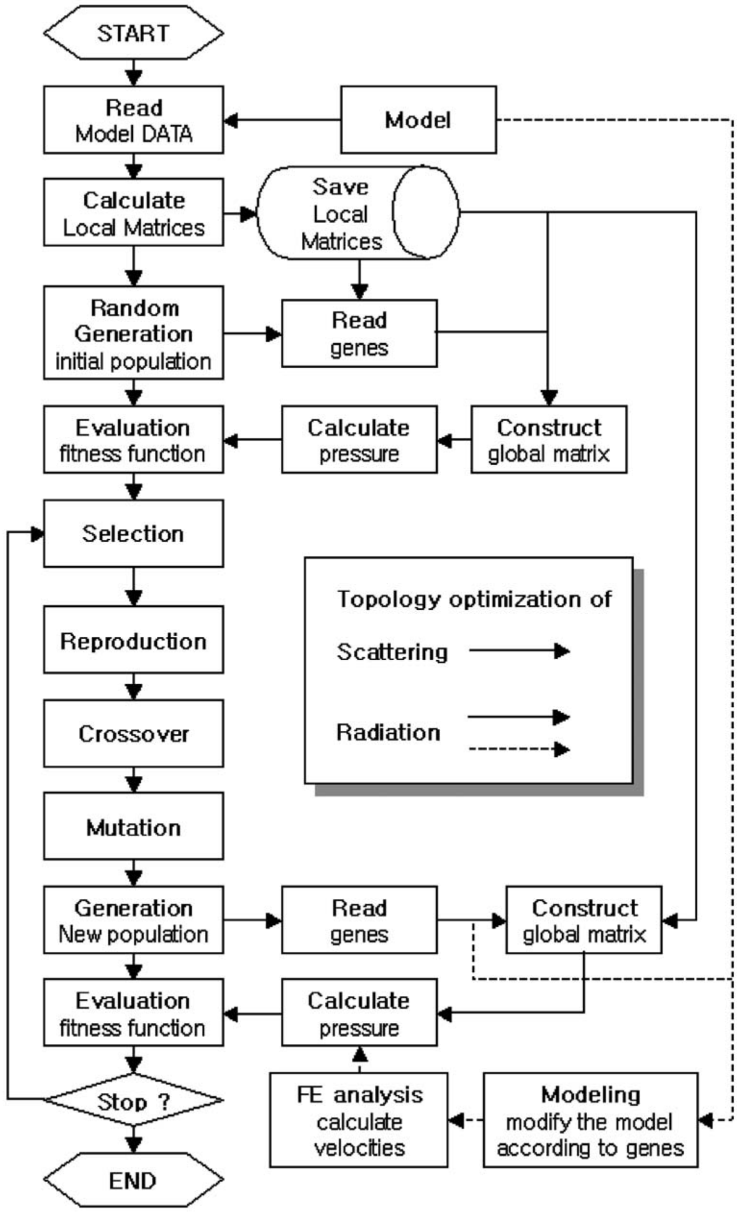

Fig. 3. Flow chart for the topology optimization of radiation and scattering of sound from thin-body.

imported, and the element matrices are calculated by using those data. After calculation of the element matrices, the program starts finding the best topology of the structure using GA.

At the outset of GA, the initial population is generated randomly. Each chromosome comprises a number of genes. In this research, a gene denotes the existence of a corresponding element, 0 means no element and 1 means an element exists.

For the function evaluation, the homologous layers of zero genes are excluded from the element matrices and the other layers are added to construct the global matrix. For the scattering problem, the fitness functions, acoustic pressures at the field points, are easily achieved using this global matrix. For the radiation problem, however, the surface velocity of the structure is also necessary for the calculation of the pressures at the field points. So acTop modifies the FE model according to the genes and run the FE program automatically. By reading the results of FE analysis, the velocities, the pressures at the field points are calculated as the fitness functions of the radiation problem.

Using the good genes selected from the comparisons of the fitness, the GA operators, such as crossover, mutation, and reproduction, generate the next population. By repeating those procedures, GA finds the best chromosome denoting the best topology of the holes on the design surface.

4. Numerical example

4.1. Model description

As a numerical example for the topology optimization, a small hexahedral box is considered. Although the model shown in Fig. 4 is completely closed, some holes will be made on the upper surface by using the topology optimization technique. Therefore the model will be opened by holes and the sound waves from the source will be scattered and diffracted through holes. There are many applications that have a similar configuration to above example. For instance, many

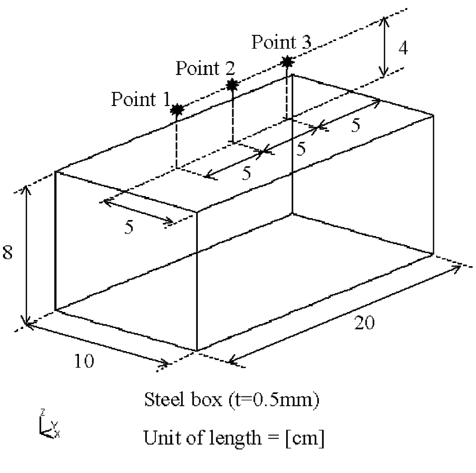

Fig. 4. Elementary model: a simple hexahedral box.

Table 1
Parameters used for the box model

Type	Value	Adjusted value
Geometry		
Width	10 cm	10
Length	20 cm	20
Height	8 cm	8
Thickness	0.5 mm	0.05
Material property—structure		
Young's modulus	210 GPa	$2.1 \times 10^{+9}$
Poisson ratio	0.33	0.33
Structural density	$7850\,kg/m^3$	7.85×10^{-6}
Material property—fluid		
Fluid density	$1.2\,kg/m^3$	1.2×10^{-6}
Sound speed	340 m/s	$3.4 \times 10^{+4}$

musical instruments such as guitar and violin are composed of a box with holes basically, even if their actual shapes are more complex. Also home appliances are similar problems.

As a reference, the modeling parameters such as the dimension of geometry and material properties are shown in Table 1. Since the centimeter scale was used for the modeling, the parameters were adjusted with respect to the scale.

4.2. Topology optimization of the scattering problems

4.2.1. Preliminary studies

As shown in Fig. 5, to simulate the scattering problem, the acoustic point source is located at the corner inside of the box and the three field points in the near fields stand over the upper surface (gray part). The box is fixed by four corners of the lower surface and assumed it is so rigid that no vibration is generated by the acoustic source. Since the box is modeled using the shell elements with no velocity, this example is a typical problem of the scattering of sound from a thin-body.

To set the formulation of optimization, preliminary studies are carried out. For the investigation of acoustic characteristics of the boxes with different holes, four basic models shown in Fig. 6 are considered. For comparisons, each model is made to have the almost same area of the holes, about 8–10% of the area of the upper surface.

Fig. 7 indicates the results of acoustic analyses of four models. All results have the first peak near 800 Hz. The high pressure arising in a low frequency range is a natural result for the scattering since the propagated sound from a source is inversely proportional to the frequency with an exponential rate, and the scattering effect is insignificant in a low frequency band. The peak around 800 Hz, however, is due to the first mode of the acoustic cavity in the box. The FE analysis of the acoustic cavity in the box proffers the eigenvalues and eigenvectors shown in Fig. 8. Even if the basic models in Fig. 6 have different holes, the global shape of cavity, which is the

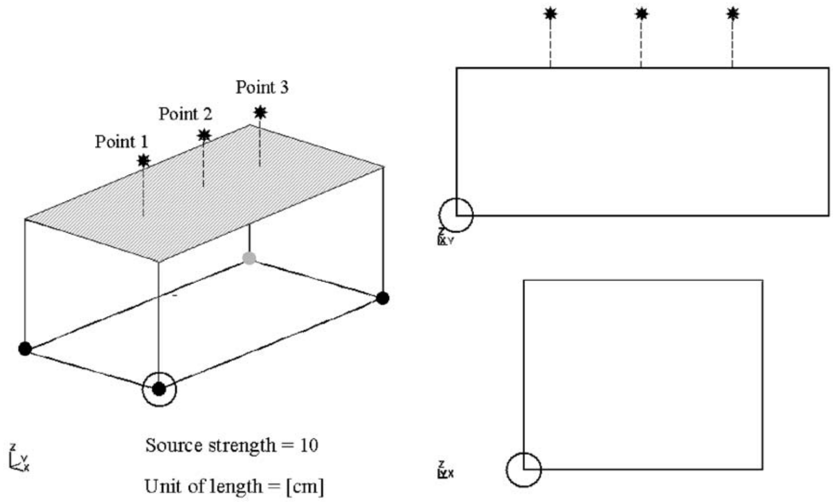

Fig. 5. Simple box with an acoustic point source located inside (○, acoustic point source, ★, field points, ●, fixed boundary points).

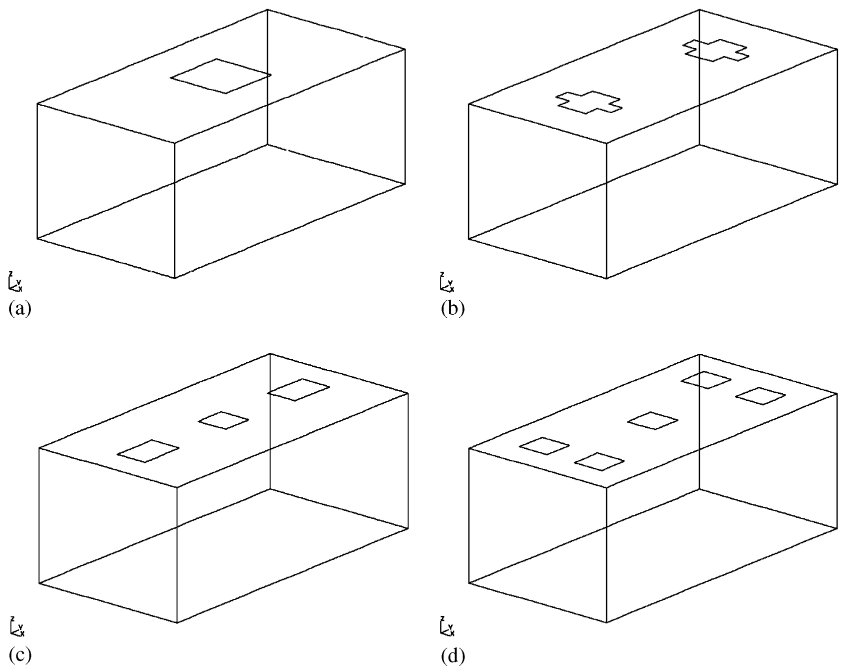

Fig. 6. Basic models for the preliminary studies: (a) model 1, (b) model 2, (c) model 3, (d) model 4.

main factors to determine the eigenvalues, of every model is same. Anyway, model 3 has the smallest peak value among the preliminary models. The peak value of the model 3 is 74.9 dB and the peak appears at 810 Hz.

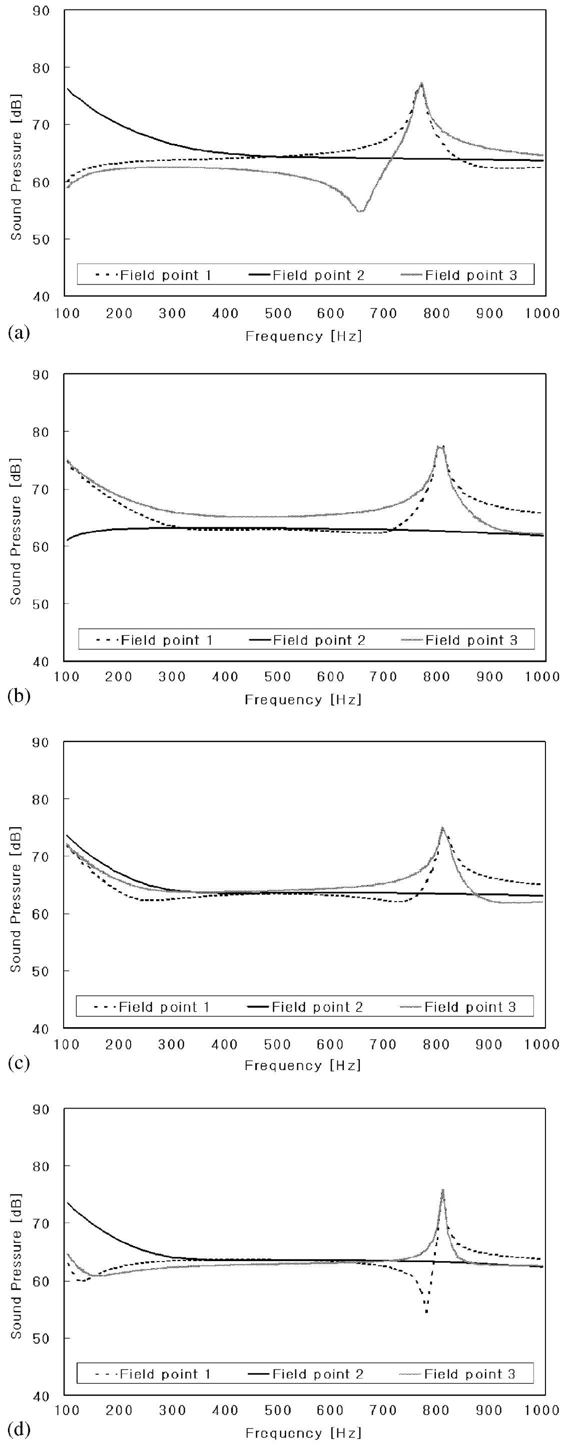

Fig. 7. Analysis results of the preliminary studies for the scattering problem: (a) model 1, (b) model 2, (c) model 3, (d) model 4.

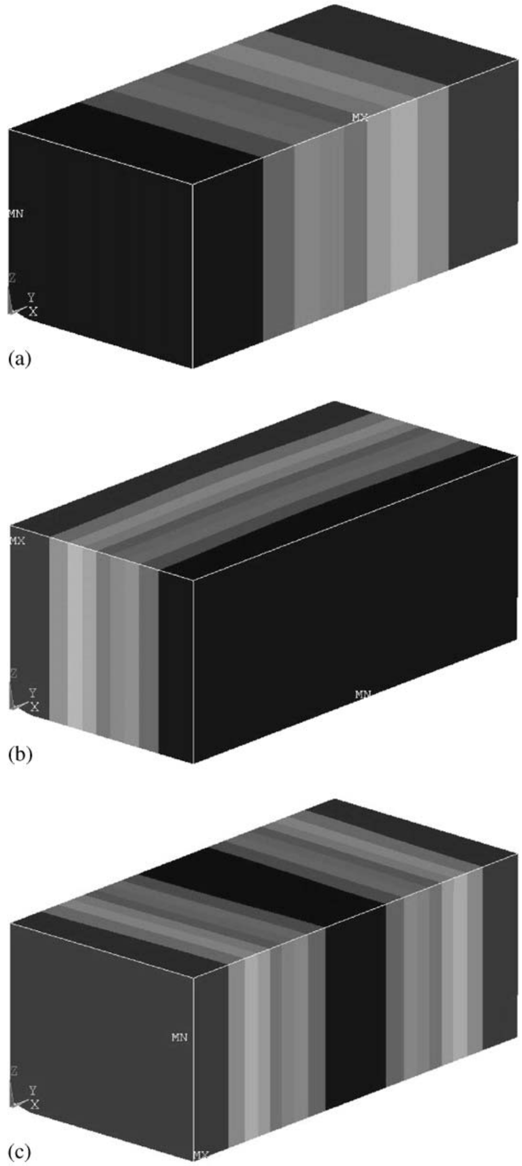

Fig. 8. Results of the acoustic modal analysis for the box: (a) first mode: 817.87 Hz, (b) second mode: 1707.0 Hz, (c) third mode: 1907.3 Hz.

4.2.2. Optimization

The frequency band from 750 to 850 Hz is decided as a frequency range of interest for the optimization. In the optimization formulation, the objective is the minimization of the maximum pressure in the frequency range of interesting, and the constraint is that the total area of the holes must be 9% of the area of upper surface with 1% variation. To state

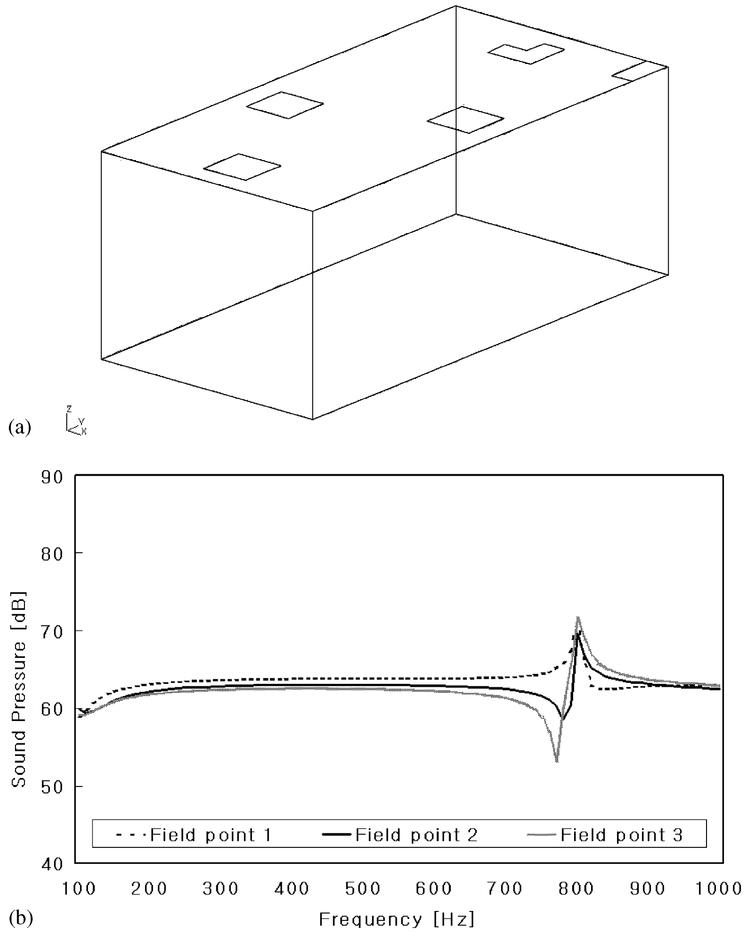

Fig. 9. Optimum design for the scattering problem and its analysis results: (a) optimum design, (b) analysis results of optimum design.

the optimization formulation,

$$\begin{array}{ll} \text{Minimize} & \text{maximum}|P(\hat{x}_i, f)| \\ \text{Subject to} & 0.08A_{ds} \leqslant A_{hole} \leqslant 0.10A_{ds}. \end{array} \tag{6}$$

In Eq. (6), $\hat{x}_i$ is the ith field point ($i = 1, \ldots, 3$ in this example), f is a frequency in the frequency range of interest, A_{ds} is a total area of the design surface, and A_{hole} is a total area of the holes. After finishing the optimization procedures, acTop suggests the optimum design. Fig. 9 represents the optimum design obtained through topology optimization of scattering problem and analysis results of the optimum design, respectively.

The peak value of the optimum design is 71.6 dB and appears at 800 Hz. In Table 2, the biggest peak values within frequency range of interest of the preliminary models and the optimum model.

Table 2
The biggest peak values and the frequencies for the scattering problem

Model	Peak value (dB)	Frequency (Hz)
Model 1	77.1	770
Model 2	77.3	800
Model 3	74.9	810
Model 4	75.7	810
Optimum design	71.6	800

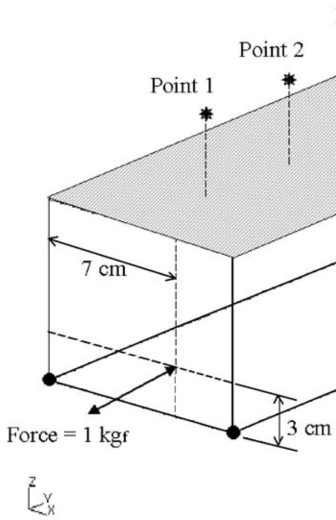

Fig. 10. Simple box with an exciting force applied on the front surface (◀—▶, exciting force, ★, field points, ●, fixed boundary points).

4.3. Topology optimization of the radiation problems

4.3.1. Preliminary studies

The discussion in this section is externally semi-coupled problems where the structural vibration generates sound, but is not influenced by the acoustic medium. As an example of the radiation of sound from thin-body, the same models are used. The elementary model of the radiation problem has the same shapes, boundary conditions, and the field points of the model used for the scattering problem, except the forcing condition and 2% of structural damping. Instead of the sound source, a force, 1 kgf, is applied to vibrate the structure as shown in Fig. 10. The velocity of the surface caused by applied force generates the wave fluctuation of the acoustic pressure, and the wave is propagated to the field points. This kind of radiation problem is called vibroacoustics, and the radiated sound from vibrating structure is called structure-bone sound.

Contrary to the scattering analysis, the radiation problem needs not only acoustic analysis but also structural analysis. In general, FEM and BEM are associated with the radiation problem. The FEM is commonly used to compute the vibration of the structure emitting the sound, and the BEM to predict the generated sound. Therefore, the structural analysis is performed by FEM and

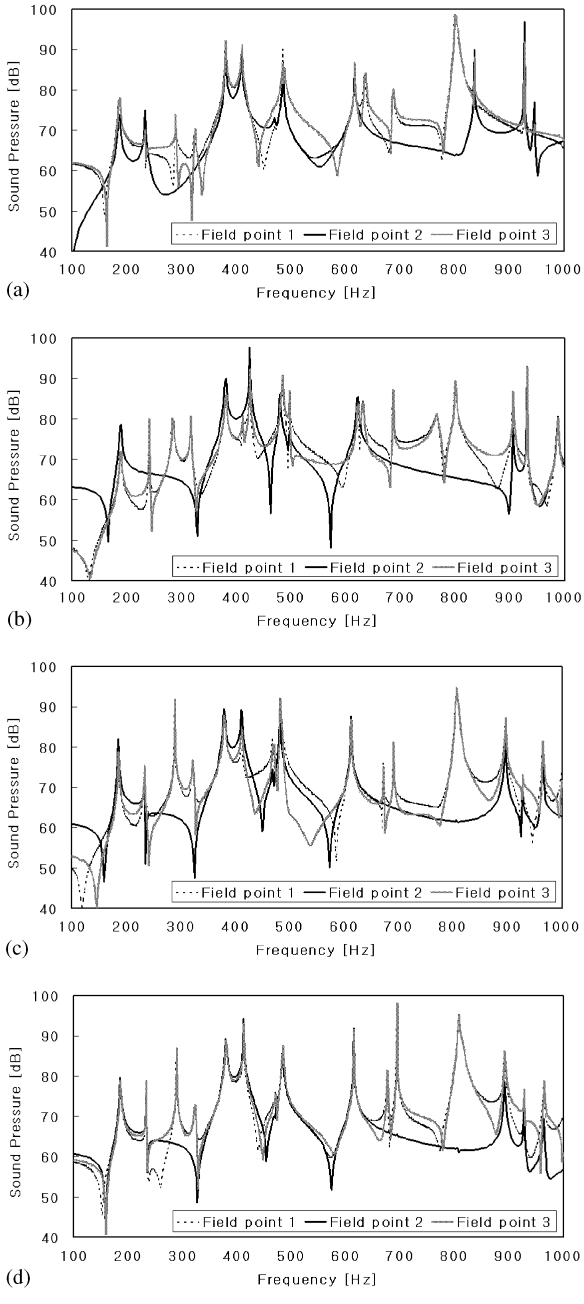

Fig. 11. Analysis results of the preliminary study for the radiation problem: (a) model 1, (b) model 2, (c) model 3, (d) model 4.

the acoustic analysis by BEM. In this research, MSC/NASTRAN, a commercial FEA program, is used to calculate the velocities of the vibrated structure, and acTop is used to predict the acoustic pressures at the field points using the velocities.

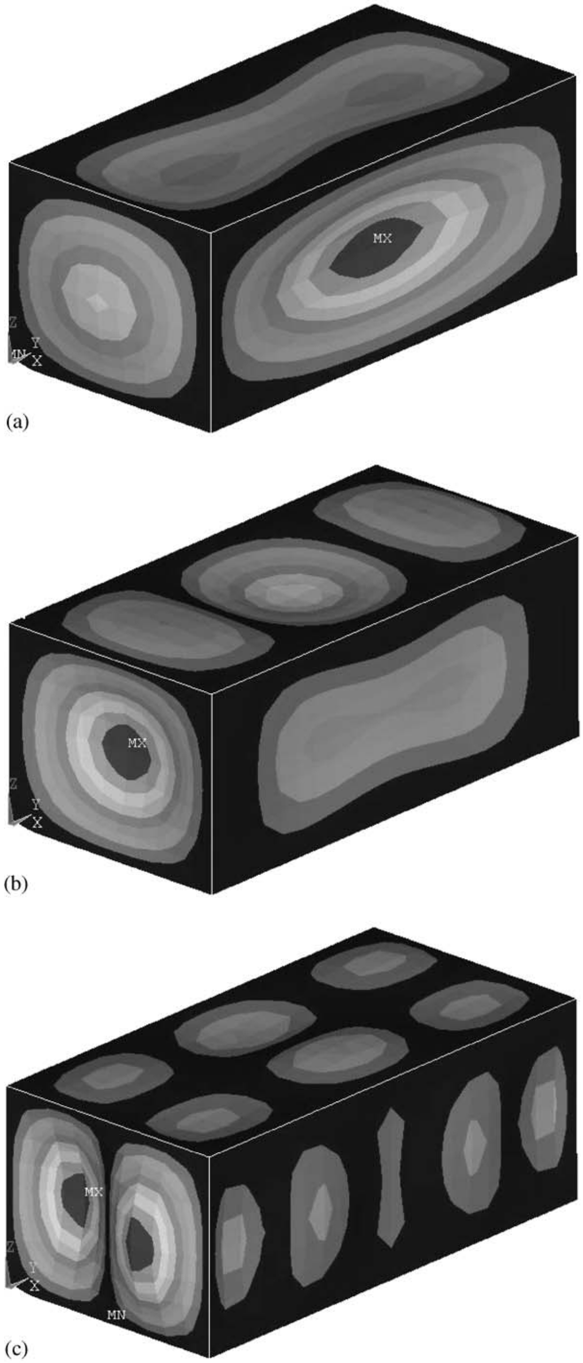

Fig. 12. Several important results of the structural modal analysis. (a) First bending of the side surface: 380.18 Hz, (b) first bending of the front surface: 419.71 Hz, (c) second bending of the front surface: 820.45 Hz.

For the preliminary studies, the models shown in Fig. 6 are used again. First, the calculations of the velocities are performed and the acoustic pressures are achieved using these velocities. The acoustic pressures are shown in Fig. 11.

Each graph in Fig. 11 illustrates several peaks of sound pressures. And those peaks can be classified into two main groups as the sweeping generalization of the results. Two groups appear around 400–800 Hz, respectively. From the structural modal analysis of the elementary model, shown in Fig. 12, it is found that the peaks are related to the structural modes. Especially, the bending modes of the front surface and the side surface in the viewpoint of the Fig. 12 have a heavy connection with the field point pressures because of the forcing condition applied. Although some peaks appear around the frequencies of the bending mode of the upper surface such as 300–500 Hz, the peak values at those frequencies are relatively small.

4.3.2. Optimization

The frequency band from 350 to 450 Hz is decided as a frequency range of interest for optimization. The optimization of the radiation problem has the same formulation used in the previous section; the objective is the minimization of the maximum pressure in the frequency

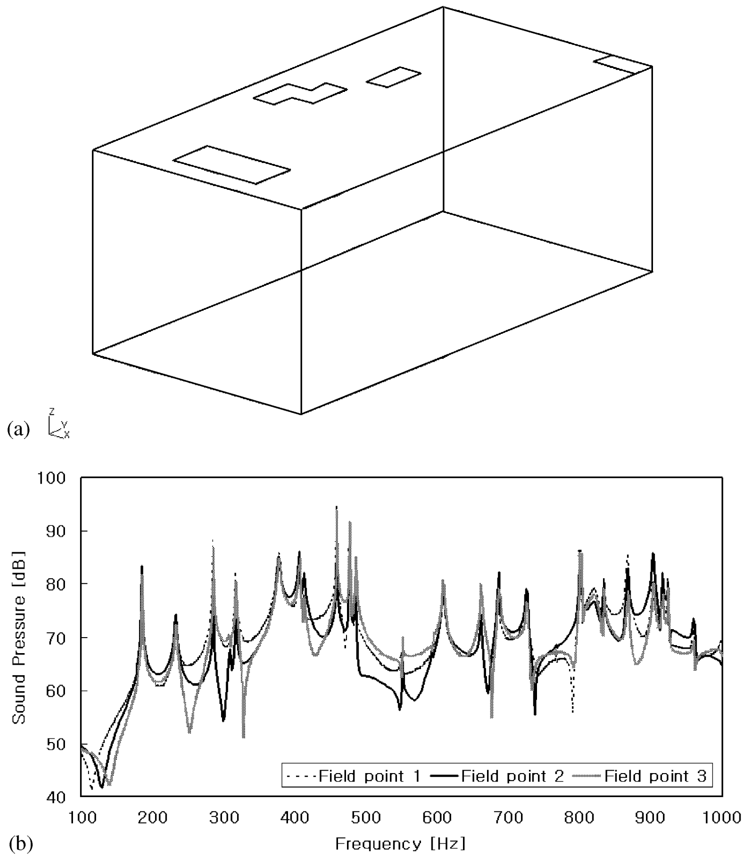

Fig. 13. Optimum design for the radiation problem and its analysis results: (a) optimum design, (b) analysis results of optimum design.

Table 3
The biggest peak values and the frequencies for the radiation problem

Model	Peak value (dB)	Frequency (Hz)
Model 1	92.0	380
Model 2	97.6	424
Model 3	89.5	378
Model 4	94.3	412
Optimum design	86.1	406

range of interest, and the constraint is that the total area of the holes must be 9% of the design space with 1% variation. To state the optimization formulation,

$$\begin{aligned} &\text{Minimize} \quad \text{maximum}|P(\hat{x}_i, f)| \\ &\text{Subject to} \quad 0.08A_{ds} \leqslant A_{hole} \leqslant 0.10A_{ds}. \end{aligned} \tag{7}$$

Noting that the notations used in Eqs. (6) and (7) are the same.

After finishing the optimization procedures, acTop suggests the optimum design. Fig. 13 shows the optimum design of radiation problem and the analysis results of the optimum design, respectively.

The peak value of the optimum design around 400 Hz is 86.1 dB at 406 Hz. Compared with the minimum peak value around 400 Hz in the preliminary studies, which is the peak value of the model 3 and is 89.5 at 378 Hz, the optimum model has very reduced pressure level at the first peak. The biggest peak values within frequency range of interest of the preliminary models and the optimum model are shown in Table 3.

5. Conclusion

Based on the normal derivative integral equation and the genetic algorithms, the topology optimization method is developed in this paper for the radiation and scattering of sound from thin-body structures. Since there has been no study reported yet on the topology optimization in acoustic fields, the proposed method should be very attractive for acoustic engineers. Using a simple hexahedral box model, the topology optimization proposed in this research is validated for both the radiation and scattering problems. In numerical examples, the peak values of the optimum design are reduced significantly in the frequencies of interest decided in the optimization formulation. In the frequencies out of the range, it is possible the sound pressure level is increased to minimize the sound pressure in the frequency range of interest. To avoid this phenomenon, engineer must extend the frequency range of interest. It has no problem in technical point of view. For the decision of excitation frequencies, it is not important only the frequency range of interest but also intervals of discretized frequency steps. Unless the continuum approaches are used, the large intervals of frequencies can make the actual peaks missed because it is possible that a peak disappear between the excitation frequencies. Although the damping of structure makes the responses smooth for the radiation problems and helps missing of peaks, the structural damping has no meaning for the scattering in air. Instead of damping coefficient used in the numerical analysis of structures, the distance from a source point to a measuring point plays a role of damping in the numerical analysis of acoustics such as BEM. Anyway, to get the all peaks in the frequency range of interest, small intervals of frequencies should be better. The larger range of frequency and the smaller intervals of excitation frequencies, however, should lead the increase of computation time. Hence, the user must decide the frequency range of interest and the intervals of excitation frequencies carefully.

In this research, all examples are set as a near field problem to see the local effects of the holes more clearly, and the objectives of the optimization are the magnitude of the sound pressure. For a real implementation, however, the sound power should be better than the sound pressure. To use the sound power as an objective, a further research has to be carried out.

As shown in Figs. 9(a) and 13(a), models of the optimum design, the final shape of topology optimization is generally rough because of the element size. It means the employment of the fine mesh can make the fine shape of holes. The fine mesh, however, doesn't lead only fine design but also high computation. There is a more elegant way to get a fine design. It is the shape design sensitivity analysis (DSA) technique for the thin-body acoustics proposed by Lee and Wang [16]. Using the shape DSA, engineer can predict how much pressure peak changes if the position and shape of holes are slightly changed due to manufacturing problems for example.

Anyway, although the result of topology optimization needs more interpretation, to find a fine design, this result shows the global tendency of the acoustic characteristics to a design engineer. From the result of topology optimization, a design engineer can get the basic concept of hole position and shape as an initial design. Hence, acTop, developed program for the topology optimization, can help an engineer to understand the acoustic system clearly and to design an efficient acoustic system easily.

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